Physics of $\eta' \to \pi^+\pi^-\eta$ and $\eta' \to \pi^+\pi^-\pi^0$ decays

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Abstract. The article describes experimental status of the $\eta' \to \pi^+\pi^-\eta$ and $\eta' \to \pi^+\pi^-\pi^0$ decays. A theoretical framework used for description of the decays mechanism is also reviewed. The possibilities for the measurements with WASA-at-COSY are mentioned.

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EXPERIMENTAL OVERVIEW

The $\eta' \to \pi^+\pi^-\eta$ decay with branching ratio (BR) 44.5% [1] is the main decay mode of the $\eta'(958)$ meson. The experimental studies of the reaction mechanism are based on the following data samples: 1400 events from [2] (1974), 6700 events from [3] (2000). The most recent results are from VES experiment with two data sets of 14600 and 7000 events collected in two different η' production reactions [4] (2006). The decay $\eta' \to \pi^+\pi^-\pi^0$ is rare since it violates isospin. There exists only a weak limit $BR \leq 5\%$ (90% CL) obtained long time ago [5]. These hadronic decays provide a tool for studies of fundamental symmetries of QCD as explained in the following.

SYMMETRIES

The physical η', η and π^0 mesons are not pure isospin states $\widetilde{\eta}'$, $\widetilde{\eta}$ ($I = 0$) and $\widetilde{\pi}^0$ ($I = 1$), mainly due to existence of the quark mass term in QCD Hamiltonian, so the transitions between them are possible. Considering only isospin $\pi^0 - \eta$ mixing, related to light quark mass difference ($m_d - m_u$), one can write:

$$\begin{aligned} \pi^0 &= \cos(\theta_{\pi\eta})\widetilde{\pi}^0 - \sin(\theta_{\pi\eta})\widetilde{\eta} \\ \eta &= \sin(\theta_{\pi\eta})\widetilde{\pi}^0 + \cos(\theta_{\pi\eta})\widetilde{\eta} \end{aligned}$$

where $\theta_{\pi\eta}$ is the mixing angle between π^0 and η. The mixing angle is expressed in terms of the quark masses:

$$\sin(\theta_{\pi\eta}) = \frac{\sqrt{3}}{4}\frac{m_d - m_u}{m_s - \widehat{m}},$$

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with $\widehat{m} = (m_d + m_u)/2$. One proposed way to extract the mixing angle is in hadronic decays of η' [6]. In the paper it is argued that the ratio $R = \Gamma(\eta' \to \pi^+\pi^-\pi^0)/\Gamma(\eta' \to \pi^+\pi^-\eta)$ can be related to $\theta_{\pi\eta}$ in a very simple way: $R = P\sin^2(\theta_{\pi\eta})$, where P is the phase-space factor. To extract $\theta_{\pi\eta}$ there should be two conditions fulfilled:

- The decay $\eta' \to \pi^+\pi^-\pi^0$ should follow via intermediate state $\pi^+\pi^-\eta$ and subsequent $\eta - \pi^0$ mixing.
- The amplitudes of both decays must be constant over the phase space.

Recent analysis within Chiral Unitary Approach [7] shows that the decay does not follow entirely via $\eta - \pi^0$ mixing. Moreover the decay amplitudes are not constant since resonances in the final state interaction are important. Therefore the mixing angle $\theta_{\pi\eta}$ and quark mass difference cannot be extracted in this simple way. In the following section a brief overview of the Chiral Effective Field Theory is given and in particular Chiral Unitary Approach as the physical tool to describe the hadronic decays of η' is introduced.

CHIRAL EFFECTIVE FIELD THEORY

Chiral Symmetry [8, 9] is connected with transformation of left and right handed quark fields. It holds for QCD Hamiltonian when masses of the quarks are put to zero (chiral limit). It is spontaneously broken i.e the ground state does not posses the symmetry of the Hamiltonian itself. The consequence is the existence of the massless mode, so called Goldstone Bosons – the octet of the pseudoscalar mesons. Nevertheless η' in chiral limit remains massive as a consequence of $U(1)$ axial anomaly [10] and it is close related to it. Chiral symmetry is also explicitly broken by the masses of the quarks what leads to the non-zero masses of the pseudoscalar mesons. with help comes Partially Conserved Axial Current (PCAC) hypothesis, which says that the quark mass scale is small in comparison to the hadron mass scale. The symmetry breaking effects are small and one can use a perturbative approach at low energy. One can use Effective Field Theory [11] and construct the Chiral Effective Field Theory - *Chiral Perturbation Theory* (CHPT).

We know that low energy QCD should be independent of the short distance physics. So, one derives an effective Hamiltonian which consists of: a long range part with ultraviolet cutoff - to exclude high momentum states and a set of contact terms - to mimic the short distance behavior. Each such contact term, derived by the symmetry constrains, consists of a local coupling constant multiplied by the local operator. Now we can mimic with arbitrary precision the low energy data sets. But a problem arises when one want to generate resonances – the perturbative series just breaks down and does not converge. One possible way to generate resonances is to use non perturbative relativistic coupled channels via Bethe-Salpeter Equation (BSE) as it is done in the Chiral Unitary Approach [12]. The η' meson is included in this approach as a dynamical degree of freedom explicitly.

Based on the described framework and on the available data, from which one has to extract the chiral parameters, one can predict distributions of the products of the hadronic η' decays. In the Fig. 1 a predicted shape of the Dalitz plot for the $\eta' \to \pi\pi\eta$ decay is

shown. Influence of $a_0(980)$ ($I=1$) Fig. 1a or $f_0(980)/\sigma$ ($I=0$) Fig. 1b in the final state can be observed by different population of the Dalitz plot. The limited statistics of the existing experimental data does not allow to distinguish between the two possible scenarios since the difference is small (the total variation of the Dalitz plot densities is only 20%).

The fits to all existing data on hadronic η and η' decays, including the latest VES data [4], lead to predictions of surprisingly large branching ratio of the isospin violating decay $\eta' \to \pi^+\pi^-\pi^0$. The predicted value of 1.8% is more than one order of magnitude larger than the neutral mode $\eta' \to \pi^0\pi^0\pi^0$. Such large branching ratio is explained by $\rho^{\pm}(770)$ dominance and can be observed also in the Dalitz plot in Fig. 2. The experimental search for $\eta' \to \pi^+\pi^-\pi^0$ is difficult due to three pion background which accompanies production of η'.

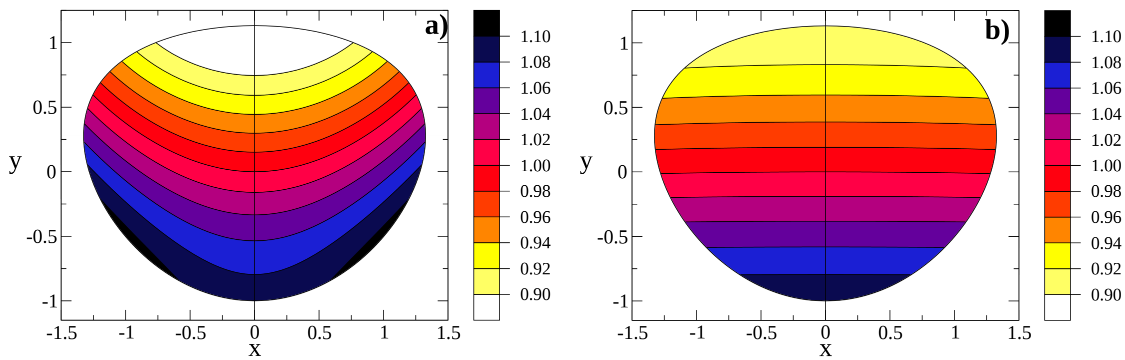

FIGURE 1. Predicted Dalitz Plot for the $\eta' \to \pi\pi\eta$ decay: a) with $a_0(980)$ dominance, b) with $f_0(980)/\sigma$ dominance [13].

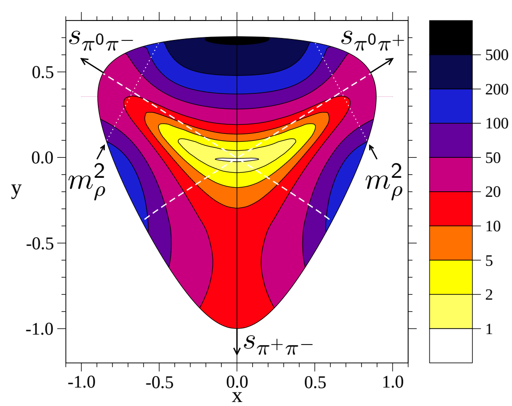

FIGURE 2. Predicted Dalitz Plot for the $\eta' \to \pi^+\pi^-\pi^0$, one sees $\rho^{\pm}(770)$ dominance [12].

SUMMARY AND OUTLOOK

The $\eta' \to \pi^+\pi^-\eta$ and $\eta' \to \pi^+\pi^-\pi^0$ decays, as described above, give unique scientific opportunity to study symmetries in nature and to provide experimental verification of the sophisticated theoretical predictions as the Chiral Unitary Approach and to reveal the driving mechanism of the decays. The experimental situation of the considered decays

was also reviewed. The need for the further data was indicated. When running WASA-at-COSY[14] at its designed luminosity of $L = 10^{32}\text{cm}^{-2}\text{s}^{-1}$ one could get 90000 accepted events per day for the $\eta' \to \pi^+\pi^-\eta$ decay – more than the present world statistics. Newly commissioned WASA-at-COSY experiment is on the way to take exclusive data on η' decays.

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